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Title: Modeling adhesive debonding using the shim layer modeling approach

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Modeling adhesive debonding using the shim layer modeling approach

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SUMMARY

There are multiple possible methods for modeling adhesive debonding in finite element simulations. However, many of these techniques are incapable of meeting all of the requirements of a thermomechanical simulation involving assemblies with thin layers of elastomeric potting materials. In this paper, these requirements are first identified, then one particular method, termed the "shim layer" modeling approach, is described. This modeling approach is capable of meeting all of the modeling requirements.

1 MODEL CAPABILITIES REQUIRED FOR THERMOMECHANICAL ANALYSIS

The following capabilities are required for thermomechanical simulations of assemblies with thin layers of elastomeric potting:

1. The potting model must simulate the mechanical behavior of the layer (that is, its tensile, compressive, and shear stiffness), in the undamaged, partially-damaged, and fully debonded states, when subjected to a general history of applied loads (including unloading, reversed loading, etc.).
2. The potting model must simulate the ability of the layer to transmit normal traction in compression and shear traction via friction (when under simultaneous normal compression) in the fully-damaged (debonded) state.
3. The potting model must simulate the thermal expansion of the layer.

4. The potting model must simulate heat conduction through the layer. Reduction of the conductivity due to separation of the adherend surfaces should also be possible.

In addition to these modeling requirements, the treatment of the potting layer must represent a mechanically-stable system throughout the evolution of debonding. Furthermore, the modeling techniques should permit a relatively coarse mesh to be used for solution efficiency - for example, permitting a single element in the through-thickness direction of the layer.

2 SHIM LAYER MODELING APPROACH

In this modeling approach, the potting layer is modeled with continuum elements using a "shim" material model. The layer is tied to one adherend and uses cohesive contact at the other interface. The behavior of the shim material for the potting layer is intentionally different from the behavior of the potting: it is stiffer in shear, as described in Appendix 2. The correct elastic stiffness of the potting is captured by the series combination of the interface and the layer stiffness. The interface captures the relatively low opening mode and shear mode stiffness while the layer behaves essentially as a shim (or spacer) with relatively high compressive and shear stiffness.

The advantages of modeling the potting layer in this way include:

Stability:
Elastic damage reduces the stiffness of the interface, which is the more compliant element of the series combination of the interface and layer. This results in a locally-stable softening evolution. See Appendix 4.

Energy partition:
The elastic compliance and strain energy of the layer is determined by the interface only, and not by the bulk layer. This permits an energy-based mixed-mode damage evolution criterion, which has been found to model double cantilever beam (DCB) adhesion experiments well [1].

Meshing:
This technique does not require a fine mesh for the continuum elements representing the layer, because the layer is stiff relative to the interface.

Friction:
Shear forces can be transmitted via friction under simultaneous normal compression. This is not possible with cohesive elements, and it is an important effect in many situations.

Thermal:

Thermal expansion is modeled by the continuum layer. The thermal expansion in-plane-confinement effect (resulting in 3X multiplication of linear thermal expansion in the through-thickness direction) is captured. Heat transfer is modeled via conduction through the layer, and gap conduction across the two interfaces.

3 SHIM LAYER MATERIAL MODEL

The shim layer treatment for modeling adhesive debonding of thin layers of elastomeric potting material treats the elastic behavior of the bonded joint as a property of the interface, not of the bulk layer. The layer and the interface are effectively in-series in this model. The desired behavior of the layer itself is to act as a spacer, adding insignificant shear or normal deformation relative to that developed by the compliant interface. The interface stiffness values are intended to match the actual (as-measured) stiffness of the bonded system (for example, as determined from double cantilever beam test results).

Although the shim layer must have a high normal and shear stiffness relative to the interface, it must not add any significant bending or membrane stiffness to the modeled assembly, as that would affect the deformation of the neighboring parts in ways that the actual potting does not. This requirement is not difficult to satisfy when the adherend to which the potting layer is tied is a thicker, metal component, due to the huge difference in elastic moduli.[1]

Thus, the normal (through-thickness) stiffness of the modeled layer is high and realistic (for compression), the shear stiffness of the modeled layer is high (and artificial), and these layer stiffness properties act in-series with the soft (low-stiffness) interface elastic properties.

A material model for the potting layer that produces these behaviors is defined here. The "front-slope" elastic behavior of the traction-separation constitutive model is:

$$\sigma_n = K_{nn}\delta_n \tag{1}$$

$$\sigma_s = K_{ss}\delta_s \tag{2}$$

where σ_n and σ_s are the normal and shear tractions (force per unit area) acting on an element, δ_n and δ_s are the normal and shear displacements between the separating

[1]For example, aluminum has a Young's modulus that is roughly 30,000 greater than that of Sylgard potting.

adherends, and K_{nn} and K_{ss} are the normal and shear stiffness per unit area of the layer. For a linear elastic material in a thin layer of thickness t,

$$K_{nn} = (K + 4/3G)/t \tag{3}$$

$$K_{ss} = G/t \tag{4}$$

where K and G are the bulk modulus and shear moduli. The elastic properties for the shim material model are determined as follows: the material's shear modulus G is chosen to be some scale factor times the actual potting material's initial shear modulus G_0. The bulk modulus for the shim material, K, is chosen to maintain same (compressive) through-thickness stiffness per unit area (K_{nn}) as the actual potting layer. Then, with G and K known, the Young's modulus and Poisson ratio (E and ν) can be calculated.

When used to model a thin layer (of thickness $t = 0.5\ mm$), and with a shear scale factor of 100, this material model will give a layer stiffness that is equal to a layer of Sylgard in the thickness direction (K_{nn}, confined compression[2]), but 99 times greater in shear (K_{ss}). However, the series combination of this layer and the cohesive contact interface (which has much lower stiffness values) is a close match to the actual behavior of the bonded assembly, which was determined from double cantilever beam (DCB) test results (see Stevens 2019 [1]). These results are summarized in Table 1.

REFERENCES

1. Ralph Robert Stevens, Amanda Jo Olsen, and Laura Gabrielle Inkret, "Potting Adhesion Investigation Using Double Cantilever Beam Tests" Los Alamos National Laboratory report LA-UR-19-26370, July 2019.

[2]The stiffness per unit area in the normal (through-thickness) direction, K_{nn}, is much smaller in tension than in compression, due to local loss of confinement (during adhesive debonding at interfaces) and nucleation and/or growth of voids within the layer.

Table 1: Elastic Properties of the Potting Material and Shim Model

Sylgard (bulk)		
Initial Shear Modulus	G_0	0.3 - 0.8 MPa
Bulk Modulus	K	1250 MPa
Shim layer		
Shear Modulus	G	33 MPa
Bulk Modulus	K	1206 MPa
Young's Modulus	E	98.1 MPa
Poisson Ratio	ν	0.4864
Normal stiffness	K_{nn}	2501 MPa/mm
Shear stiffness	K_{ss}	66.0 MPa/mm
Interface		
Normal stiffness (tension)	K_{nn}	53.8 MPa/mm
Shear stiffness	K_{ss}	0.66 MPa/mm
Series combination of shim layer and interface		
Normal stiffness	K_{nn}	52.7 MPa/mm
Shear stiffness	K_{ss}	0.65 MPa/mm

Appendix 1: Other Modeling Techniques

Cohesive elements across adherends

This is the most straightforward modeling technique and is ideal for problems that do not involve thermal effects (thermal expansion and heat conduction) and which do not subject the potting layer to compression. For example, this technique is ideal for modeling the double cantilever beam experiments. The mesh for this modeling technique is illustrated in Figure 1. The cohesive elements are tied to each of the adherend surfaces and remain tied even after becoming fully damaged; there is no contact interaction. In this model, the cohesive elements represent the behavior of the bulk layer *and* the two interfaces. This modeling method has some advantages but cannot meet all of the requirements for a thermomechanical simulation:

- \+ It exhibits the best solution accuracy, as no damping is required for stability.
- \+ It exhibits the best solution efficiency and stability, permiting large time steps.
- \- It is incapable of modeling heat transfer by conduction.
- \- It is incapable of modeling thermal expansion.
- \- Compressive stress can be carried by the joint after debonding, but the approach is incapable of modeling shear tractions transmitted via friction.

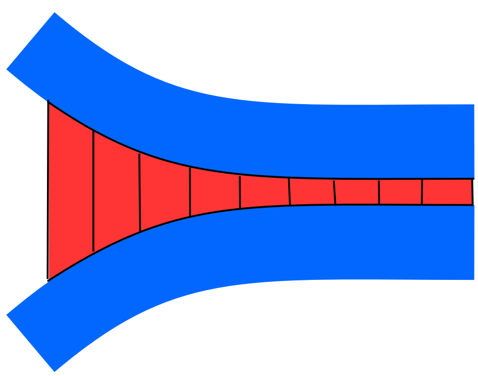

Figure 1: Cohesive elements (red), tied to both adherends (blue). The cohesive elements obey a traction-separation model, driven by the relative normal and shear displacements of the adherends.

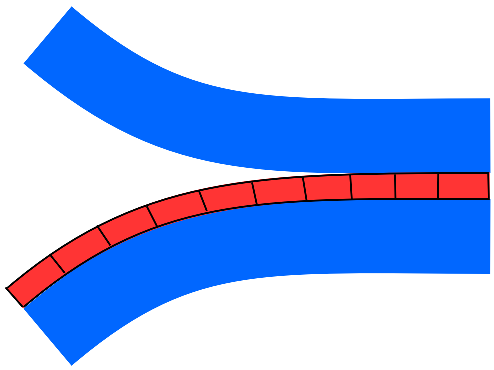

Figure 2: Continuum elements (red), tied to one adherend (blue) and interacting with the other adherend through a cohesive contact interface condition. The cohesive contact obeys a traction-separation model, driven by the relative normal and shear displacements across the contact interface.

Cohesive contact, in-series with layer

This technique is also simple, but has proven to be hard to use due to stability issues. With this modeling technique, the potting layer is modeled with continuum elements using a potting constitutive model. One or both interfaces are modeled with cohesive contact (or zero-thickness cohesive elements). The mesh for this technique is illustrated in Figure 2. With this modeling approach, the high shear compliance of the potting layer is represented by the continuum elements and the potting material model, not by the interface. This leads to some practical difficulties:

- This method can be unstable in shear, due to low shear stiffness of the layer relative to the interface. The stability issue is explained in Appendix 4.
- Energy-based mixed-mode damage evolution rule cannot be used, because the traction-separation model governs the behavior of the cohesive contact interface; the behavior of the layer, which stores most of the energy (shear strain energy), is represented by the continuum elements and is not governed by a traction-separation model.
- This treatment exhibits a strong sensitivity to the mesh refinement of the layer. When a coarse mesh is used, this method can result in a mesh-dependent "every-other-node" debonding pattern (see Figure 3) and does not reproduce the expected normal-mode traction-separation behavior.[3]

[3]Because many elastomeric potting materials, such as Sylgard, are considered an "incompressible rubber," with a bulk modulus that is more than 2000 times greater than its shear modulus, they tend to deform into volume-conserving (isochoric) configurations. When a thin, bonded layer is

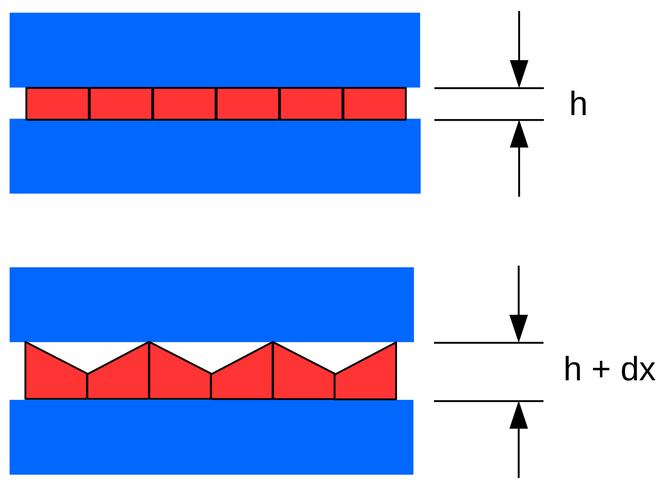

Figure 3: A mesh-dependent deformation pattern often produced in debonding simulations using a nearly-incompressible material model for the layer (continuum elements). In this example, a pure opening-mode displacement causes the mesh to deform in such a way that every other node debonds; this deformed configuration permits an opening-mode separation greater than the traction-separation model's damage initiation criterion, even though the damage initiation criterion has not yet been reached at every other node. Although the deformation pattern looks like hourglassing, this pattern has been observed with fully-integrated elements.

Cohesive contact only; layer is not modeled

This technique uses cohesive contact acting between the adherends "across" the (empty) layer gap. The layer is not meshed. The *CLEARANCE contact option is used to permit contact with a specified gap. The potting layer stiffness is modeled as an interface property of the contact pair.

+ Stable
+ Gap conductance can account for layer thickness
- No thermal expansion of layer
- No heat capacity of layer, also missing mass
- Debonding spatial resolution depends on the mesh of the adherends

Doubled elements, mechanical / heat transfer split

In this technique, the potting layer is modeled with *both* cohesive elements and continuum elements. These elements share nodes, and therefore act in parallel. The mesh for this approach is the same as that illustrated in Figure 1. The cohesive elements govern the stiffness, including opening, shear+opening, and compression. The continuum elements use a "soft" material model and carry no stress, but do handle the heat conduction.

- There is no thermal expansion of the layer. Cohesive elements cannot simulate this; the continuum elements can but because their elastic modulus is very small, their thermal expansion is negated by mechanical contraction.
- There is no friction after debonding.

Doubled elements, tension / compression split

This technique employs spatially-coincident elements that do *not* share nodes, so the elements act independently. Cohesive elements govern opening and shear+opening

subjected to a pure opening-mode deformation, the material develops features such as voids or periodic interfacial debonding patterns that accomodate the interfacial separation without inducing volumetric strain. A finite element model is capable of simulating these deformations, however a very fine mesh is required to resolve the localized features of the deformation. When modeled with a coarse mesh (for example, with a single linear element in the through-thickness direction), the behavior of the model can be nonphysical.

behavior, but have neglibigle stiffness in compression (using the "COMPRESSION FACTOR" option of the analysis code). The continuum elements govern compression and shear+compression, and use a potting material model. The continuum elements also have sliding/separating contact on both sides. This contact means that these elements never carry tension, but they do carry direct compression and frictionally-generated shear, and permit frictional sliding.

- Before debonding, resistance to shear (with compression) may be over- estimated because (assuming no sliding) both the cohesive elements' shear stiffness and continuum elements' shear stiffness resists shear displacement.

- The thermal strain in the continuum elements causes the layer thickness to grow or shrink; this represents an opening displacement (that is, a separation of the adherends) by the cohesive elements. The total through-thickness thermal growth is not small (compared to the opening displacement for normal-mode damage initiation).

Appendix 2: Stability

The underlying reason for difficult solution convergence with some cohesive contact modeling approaches is related to the localized softening of the bond's stiffness during the evolution of damage.

The situation can be illustrated with a simple model consisting of two springs in series, as illustrated in Figure 4. In this figure, spring 1 represents the elastic behavior of the potting layer (which is modeled with continuum elements) and spring 2 represents the "front slope" initial stiffness of the cohesive contact interface treatment. If the stiffness of the undamaging spring is small relative to the stiffness of the damaging spring ($k_1 << k_2$), an unstable condition is created as x_2 is made to continually increase (a "displacement-controlled" test of this system). When the applied force reaches the peak force for spring 2 (following its traction-separation rule), further increase of x_2 results in a discontinuous jump to a different equilibrium state (assuming zero damping). During this jump, x_1 returns to zero "instantly." There is no continuous path of equilibrium states in this example. This is a local instability: strain energy must be redistributed in the system as local softening evolves, and this redistribution occurs in the simulation with no time-dependent (damping-like) material behavior.

Because Sylgard has a very low shear modulus and the thickness of the layer is significant, the potting layer has a low shear stiffness. In modeling the potting joint using the methods described in this report, if the interface is significantly stiffer than the continuum layer, the shear response is unstable. An analysis code cannot solve for the displacements in this mechanical system without introducing damping or treating the problem dynamically.

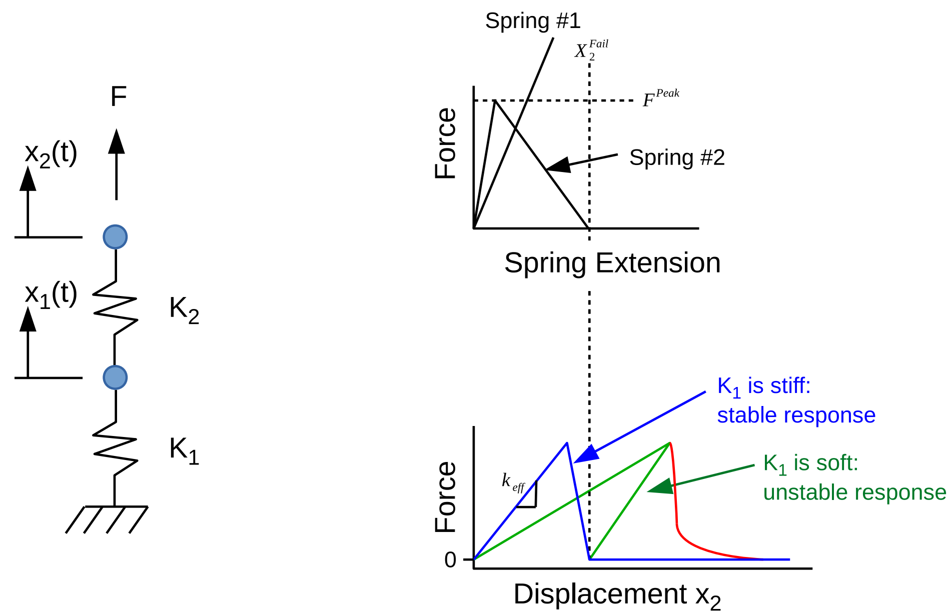

Figure 4: Two springs in series: a linear, non-failing spring k_1 and a non-linear spring k_2. The load-deflection behavior of each spring is shown in the upper-right plot. The load-deflection behavior of the system is shown in the lower-right plot, for two values of k_1. When k_1 is sufficiently compliant (relative to k_2), there is no continuous path of equilibrium states, assuming a monotonically-increasing x_2.

Appendix 3: Verification of the Shim Modeling Approach

A set of potting debonding simulation problems was used to to demonstrate that the cohesive contact modeling approach using the shim layer material model gives the same results as the cohesive element modeling approach.

The first debonding simulation is a model of a double cantilever beam model. This test was conducted at a constant temperature and the simulation results are insensitive to friction, so the problem can be solved using both modeling approaches. Both mode-1 (opening) and mode-2 (shear) were simulated. The load and opening displacement of the DCB specimen was taken as the simulation output. The results of the two modeling approaches are nearly identical, as shown in figure 5. It is noted that this is a weak test of the shim modeling approach because only the traction-separation behavior is simulated and compared; the beam stresses are not.

The second debonding simulation is a model of two hemispherical shells potted into each other. The shells have different coefficients of thermal expansion. Because cohesive elements cannot simulate thermal expansion, a CTE of zero was used for the potting material. Also, a friction coefficient of zero was used for the same reason. An axisymmetric model of this assembly was used to simulate the response to a temperature cycle, with both hot and cold excursions to exercise tension and compression, both with simultaneous shear. There is no heat conduction in this problem: the temperature of both the inner and outer hemispheres was equal to each other at all times throughout the thermal cycle.

A temperature drop of the assembly causes the inner hemisphere to shrink relative to the outer hemisphere, due to its higher coefficient of thermal expansion. This relative

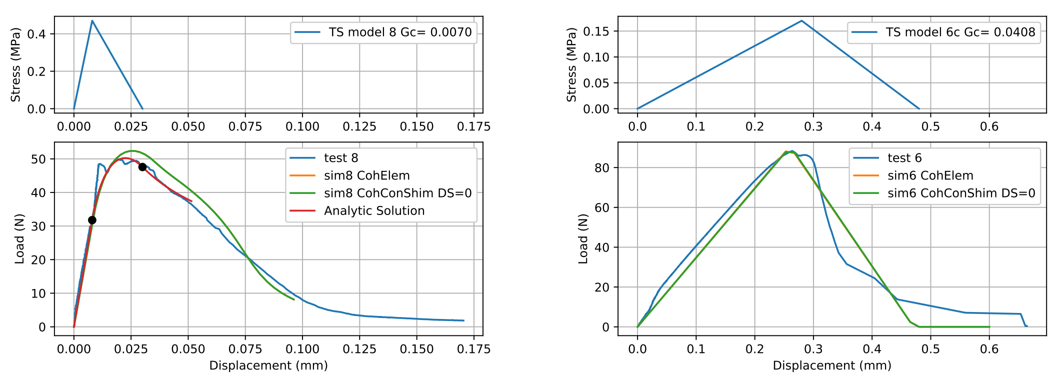

Figure 5: The applied load as a function of opening displacement for a DCB specimen. The two modeling approaches give nearly identical results. Left: opening mode. Right: shear mode.

deformation stretches and shears the potting, and eventually causes it to debond at the equator. As the temperature continues to decrease, the debonded region progresses toward the pole. The potting tractions cause stresses to be developed in the hemispheres. The largest stress in the inner hemisphere is developed near the equator at approximately the moment that debonding begins. As the debonding progresses from equator to pole, the location of the maximum stress also moves in the same manner. The magnitude of the peak stress in the inner hemisphere decreases as debonding progresses.

The cohesive element modeling approach and the cohesive contact with shim layer material model produced essentially identical results throughout the debonding evolution. The von Mises stress in the hemispheres is shown in Figure 6 at two moments during the simulation: at the moment of highest stress in the inner hemisphere, and at the moment that the simulation reached its coldest temperature.

A third debonding simulation consisted of the same potted hemisphere assembly described above, but with a mechanical pinching load applied on the outer surface of the outer hemisphere, near the pole. A symmetry boundary condition at equator was used to represent pinching of an entire sphere. For comparison against the cohesive element modeling technique, frictionless sliding was assumed, but several non-zero values of coefficient of friction were also simulated (with the cohesive contact model only) to investigate the problem's sensitivity to friction. The simulation was conducted at a constant temperature, so thermal expansion is irrelevant.

This example problem subjects the potting layer to spatially-varying regions of compression and tension, with and without simultaneous shear stress. At pole, under applied load, the potting layer is in compression and has zero shear. However, the state of stress in the potting reverses from compression to tension, and the shear stress increases, as the distance from the axis increases. Under sufficient pinching load, the potting layer reaches its damage initiation level and the two hemispheres begin to separate. The deformation and stress produced in the simulation is illustrated in Figure 7. The two debonding modeling techniques again produced essentially identical deformations and stresses in the two hemispheres.

It is interesting to note that the state of stress in the inner hemisphere is sensitive to the value of the friction coefficient. An example is shown in Figure 8. The portion of the potting layer that is directly under the applied load (a pressure applied over a region on the outer surface of the outer hemisphere, near the pole) is subjected to compression and shear; the shear traction is much greater than the adhesive strength of the potting bond, but is transmitted across the potting interface via friction, not adhesion. Note that this effect cannot be investigated with the cohesive element modeling approach.

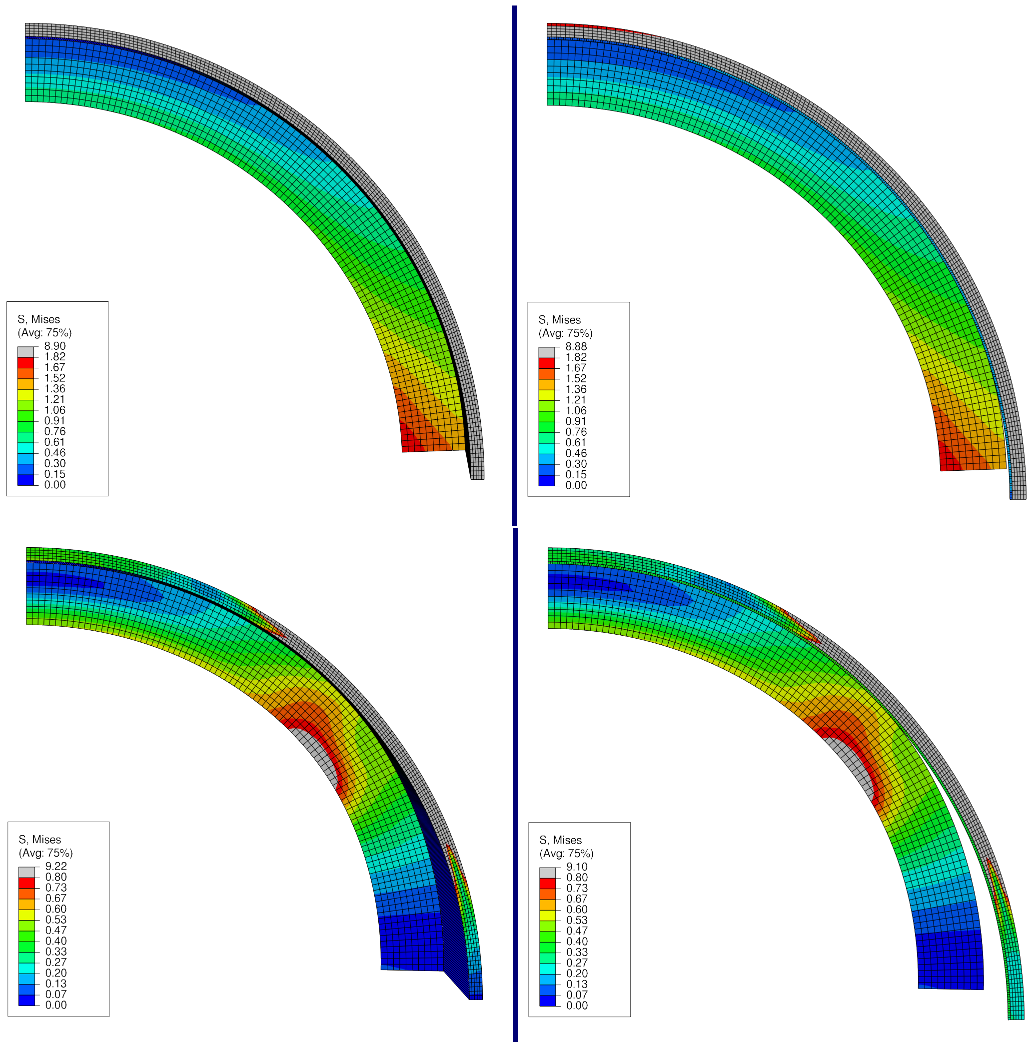

Figure 6: The von Mises stress developed in two potted hemispheres subjected to a temperature drop. Top: The von Mises stress at the moment of initiation of debonding of the potting (top) and at the coldest temperature of the thermal cycle (bottom). The model on the left uses cohesive elements, and the model on the right uses cohesive contact. The deformations have been exaggerated by 20X.

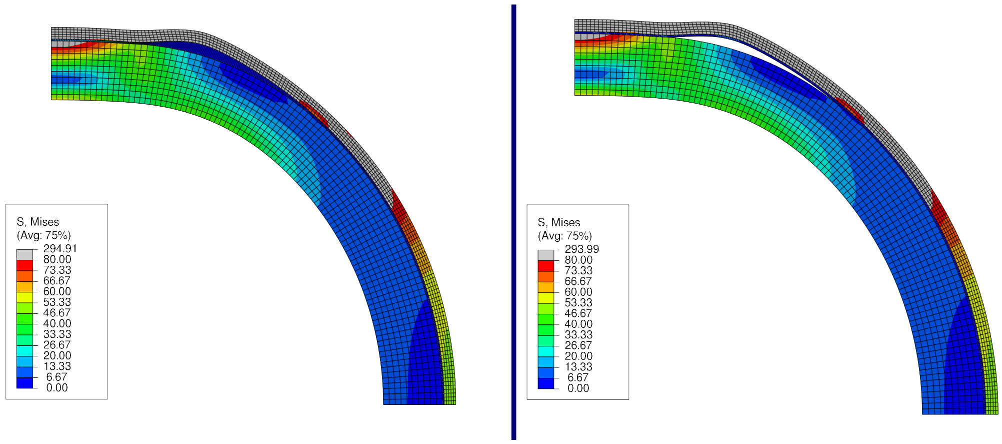

Figure 7: The von Mises stress developed in two potted hemispheres subjected to a pressure applied over the polar region of the outer hemisphere. The model on the left uses cohesive elements, and the model on the right uses cohesive contact.

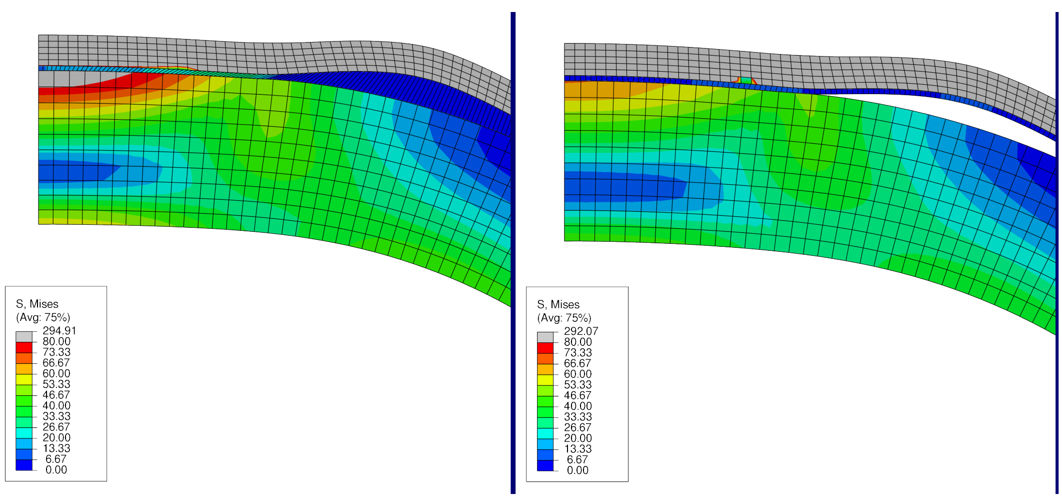

Figure 8: A close-up view of polar region, showing two variants: on the left are the same zero-friction results shown in Figure 7. On the right is a cohesive contact model with a value of friction coefficient of 0.2. The stresses developed in the inner hemisphere are affected by friction at the debonding interface.